(Preprint) AAS 17-573

JUNO TRAJECTORY REDESIGN FOLLOWING PRM CANCELLATION

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In October 2016, the Juno spacecraft was operating in 53.5-day capture orbits and final preparations were underway for a Period Reduction Maneuver (PRM) to achieve the planned 14-day science orbits. However, one week before PRM execution, a main engine propulsion system anomaly prompted an indefinite PRM delay and immediate updates to the Juno reference trajectory. This paper outlines stop-gap trajectory design activities immediately following PRM delay and longer-term trajectory redesign considerations including various possible PRM epochs, orbit period, longitude grid characteristics, and eclipse avoidance strategies that culminated in the decision to cancel PRM and adopt a new 53-day reference trajectory.

INTRODUCTION

When the Juno mission launched in August 2011, the reference trajectory for science operations at Jupiter included a Jupiter Orbit Insertion (JOI) burn to capture into a 107-day orbit and a subsequent Period Reduction Maneuver (PRM) designed to deliver the spacecraft to its final 11-day science mission orbit.[1] However, a series of safe mode entries following an otherwise successful Earth gravity assist in October 2013[2,3] led the Juno project to investigate alternate Jupiter science operations paradigms. At the conclusion of the investigation, an updated reference trajectory was approved in March 2015 that included two 53.5-day capture orbits between JOI and PRM and 14-day science orbits. Juno was placed into a 53.5-day capture orbit by a successful JOI maneuver on July 5, 2016 and final preparations for PRM were well underway in October 2016 when, one week before execution, an issue was discovered in the main engine propulsion system prompting an indefinite PRM delay and immediate updates to the Juno reference trajectory.

This paper will first outline the stop-gap trajectory design decisions that were made in the days and weeks following PRM cancellation to maintain the spacecraft in 53-day science orbits while the Juno project investigated cause and possible workarounds for the main engine propulsion system anomaly. An in-depth discussion of the longer-term reference trajectory redesign study undertaken by the Juno Navigation team is presented that includes commentary on trajectory design considerations such as PRM epoch, science orbit period, characteristics of equator-crossing longitude grid, and potential eclipse avoidance strategies. Final refinements to the redesigned reference trajectory's perijove altitude and inclination profiles implemented once it was, ultimately, decided that PRM

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would be cancelled and Juno would remain in 53-day science orbits are also detailed. Lastly, on-going trajectory design studies to yield potential future Great Red Spot (GRS) flyover and/or Earth occultation opportunities are described.

REFERENCE TRAJECTORY BACKGROUND

Since launch, the Juno project has undertaken two significant trade studies followed by complete redesigns of the orbital architecture for science operations at Jupiter. The first such investigation was prompted by a series of safe mode entries in the fall of 2013.

Safe Mode Entries Following Earth Flyby

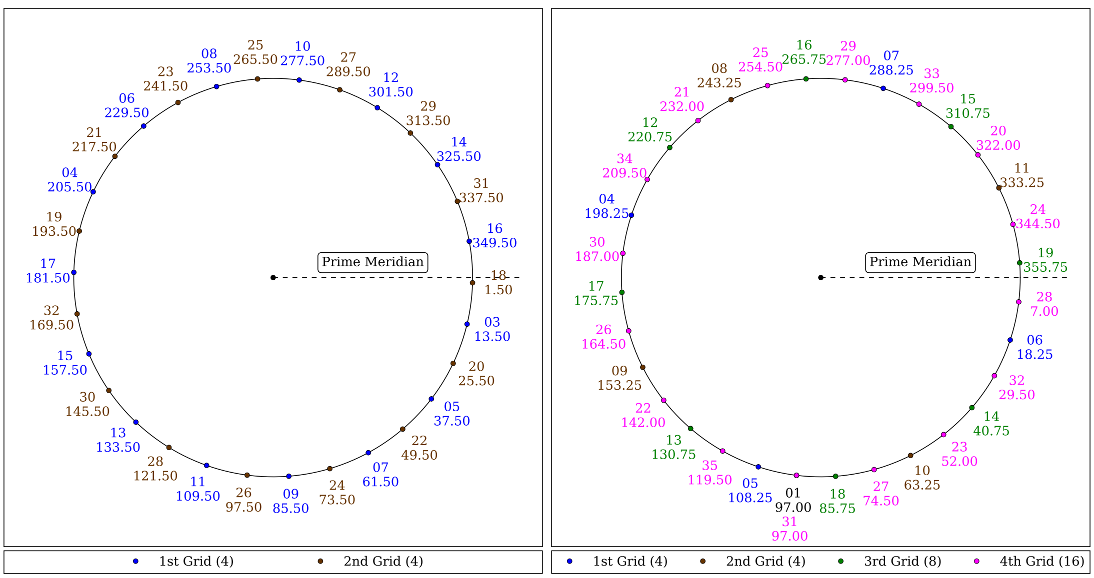
Prior to performing an Earth gravity assist on October 9, 2013, the Juno spacecraft had not experienced a single safe mode entry in over two years of post-launch operation. However, as Juno traversed Earth's shadow for an approximately 19-minute eclipse during the flyby, the battery voltage dropped below the defined fault protection limit and the spacecraft entered safe mode for the first time. Four days later, Juno entered safe mode for a second time due to an anomalous voltage reading in one of the stellar reference units (SRUs) and, just 14 hours later, a third safe mode entry was caused by the expiration of a Sun-tagup timer in the fault protection software that had not been reset following launch. While the rapid succession of safe mode entries provided the entire Juno team with valuable flight operations experience, the safing events also spurred the project to reassess the robustness of the intended plan to fly 11-day science orbits in Jupiter's harsh radiation environment. Thus, a project-wide investigation was launched in the fall of 2013 to reexamine the Jupiter orbital operations architecture, including both the 107-day capture orbit and 11-day science orbit concepts.

14-day Reference Trajectory

During the nearly 18-month investigation into alternate orbital architectures to support Jovian science operations, the Juno Navigation Team considered a variety of combinations of capture and science orbit periods. A detailed explanation of the trade space is provided by Johannesen, Pavlak, and Bordi,[4] but, in general, the mission design study had two principle goals: 1) Explore multi-capture orbit strategies – in contrast to the planned, single, 107-day capture orbit – that would enable Juno to operate its suite of instruments in the Jovian radiation environment through one or more "practice perijove passes" prior to executing PRM and entering the shorter-period science orbits and 2) Analyze candidate science orbits with periods greater than 11 days to allow the project additional response time in the event of spacecraft anomalies.

While a considerable number of Jupiter operations trajectory options were analyzed, a concept consisting of two 53.5-day capture orbits and 14-day science orbits was, ultimately, selected as the final candidate option that would be proposed to NASA Headquarters. The two 53.5-day capture orbit architecture featured a number of key advantages. Namely, it allowed for a fully-operational science perijove, PJ-01, to assess the performance of the instruments and spacecraft flight systems in the Jovian environment prior to beginning the 14-day science orbit campaign. Additionally, splitting the single 107-day capture orbit into two 53.5-day capture orbits left the PRM epoch, October 19, 2016, unchanged and, consequently, much of the detailed, epoch-specific PRM-related environmental analysis remained valid.

The 14-day science orbit campaign also offered a number of important advantages over its 11-day counterpart. The two-week orbital period provided three additional days per orbit for anomaly response while also allowing the project to develop a bi-weekly operations schedule that synced conveniently with a standard work week. Additionally, as part of its science requirements, Juno is tasked with building up an evenly-spaced longitudinal grid as its polar orbit makes subsequence passes through the Jovian equatorial plane. The 11-day science orbit strategy used 30 science passes to build an equatorial grid with 12-degree longitudinal spacing. The first 15 orbits built up the grid with 24-degree longitude spacing via subsequent science passes that are separated by 192 degrees in west longitude. The final 15 orbits completed the full grid in the same fashion following a "mid-mission shift." A significant drawback of this longitude build-up strategy is that only two, diametrically-opposed quadrants of Jupiter are observed during the first quarter of the Juno science campaign. However, 14-day science orbits enable the longitude grid to be built up in a much more "global" manner. The first four perijove passes yield an equatorial grid with 90-degree longitudinal spacing. Subsequent sets of 4, 8, and 16 perijove passes decrease the longitudinal spacing of the grid to 45, 22.5, and 11.25 degrees, respectively, providing observational opportunities throughout the mission that are uniformly distributed in longitude. A comparison of the 11- and 14-day equator-crossing west longitude grids is presented in Figure 1, with color used to differentiate the various "subgrids." After nearly 18 months of analysis, a new reference trajectory consisting of two 53.5-



(a) 11-day Orbits

(b) 14-day Orbits

Figure 1. Equator-Crossing Longitude Grids for the 11- and 14-day Reference Trajectories

day capture orbits and 34 14-day science orbits was approved by NASA Headquarters and released publicly by the Juno project in March 2015.

SHORT-TERM TRAJECTORY DESIGN DECISIONS FOLLOWING PRM DELAY

Following both hardware and software faults in the immediate lead-up to PRM and its associated perijove pass, PJ-02, the Juno Navigation Team developed a series of contingency trajectories to respond to evolving project constraints and enable the mission to continue operating under off-nominal circumstances.

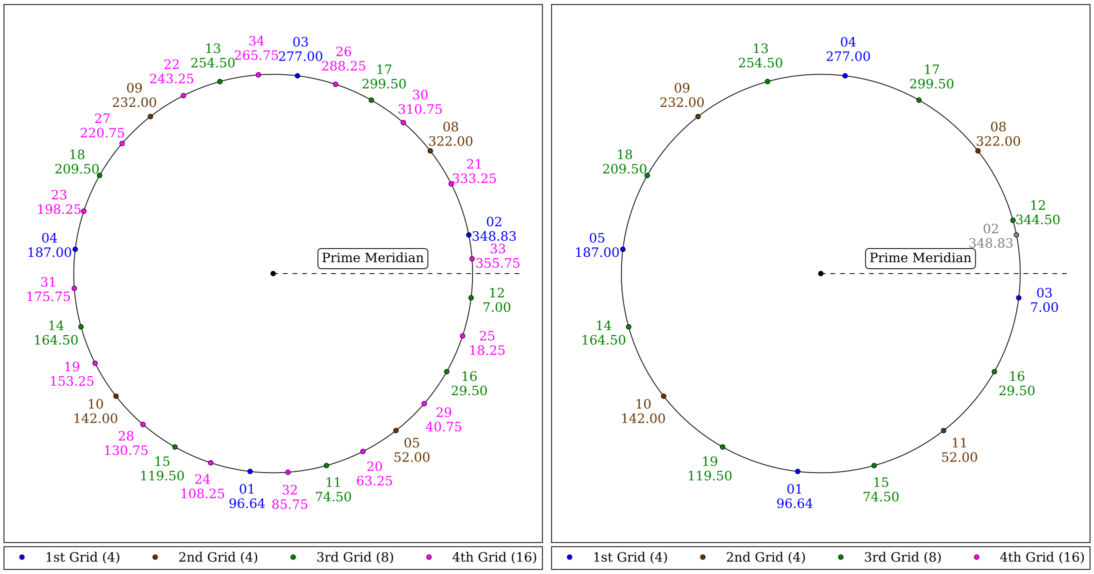
PRM Delay

Given the importance of PRM, preparations for the large main engine burn began well ahead of its October 19, 2016 execution date. The final PRM design was completed on August 1, 2016 and the spacecraft operations team began configuring Juno's onboard flight system for PRM, in earnest, on September 20, 2016 – approximately one month before the burn was to begin. The spacecraft's retractable main engine cover opened successfully two weeks before PRM and the preparations were proceeding nominally when, on October 12, 2017, a command was issued to the spacecraft to fire a pyro valve and pressurize the main engine propulsion system. Under normal circumstances, as the main engine system is pressurized, pairs of passive check valves in both the oxidizer and propellant sides of the bi-propellent system will open when the pressure differential across them becomes sufficiently large. During Juno's pre-PRM pressurization, however, onboard telemetry indicated that both check values stuck for approximately four minutes prior to opening. Additional analysis indicated, that if this "sticky" valve behavior were to manifest itself during PRM execution, the fuel-to-oxydizer mixture ratio could become suboptimal which could, in turn, have potentially dire consequences for the Juno spacecraft. Given this risk, the Juno Project decided, in conjunction with NASA, Lockheed Martin, and JPL leadership, to delay PRM indefinitely on October 14, 2016 – just 5 days prior to PRM's scheduled execution.

While the Juno project initiated an investigation into the root cause of the check valve anomaly and potential mitigation strategies, the Juno navigation team transitioned from the planned reference trajectory to a contingency trajectory that had been developed in the months preceding PRM in the event of a PRM delay. This particular case assumed that PRM would be performed at PJ-06. The contingency trajectory also assumed that Juno's PJ-02 perijove pass, originally reserved for PRM execution, would, instead, be leveraged as a traditional science pass. The equator-crossing longitude grid associated with the contingency trajectory appears in Figure 2(a). While the no-PRM PJ-02 west longitude of 348.83 degrees does not fit precisely into the evenly-spaced longitude grid, it still allots reasonable spacing between the adjacent PJ-21 and PJ-33 perijove passes. Also, note that this longitude grid begins with a successfully-completed PJ-01 science pass, in contrast to the 14-day reference grid, shown in Figure 1(b), that started at PJ-04 following a PRM-cleanup maneuver.

PJ-02 Safe Mode Entry

Juno PJ-02 operations were further complicated when the spacecraft entered safe mode on the night of October 18, 2016 – approximately 13.5 hours before Jupiter closest approach. It was later determined that the safing event was triggered by an issue in the software interface between Juno's command and data handling system and the JIRAM science instrument. As part of the onboard safe mode entry sequence, all science instruments were automatically turned off, meaning that PJ-02 could no longer be included as part of the equator-crossing longitude grid. It was desirable – both from a science and spacecraft ΔV perspective – to avoid leaving a "hole" in the longitude grid that would have to be filled with a later perijove pass, so a second contingency trajectory was developed to shift the PJ-03 target to 7 degrees west longitude and re-align all subsequent perijoves to an evenly-spaced grid as depicted in Figure 2(b). For reference, the PJ-02 longitude appears in gray. The longitude grid for the contingency trajectory following PJ-02 safe mode entry is incomplete because there was not sufficient time to complete a full 32-orbit redesign in the several hours that



(a) Following PRM Delay

(b) Following PJ02 Safe Mode Entry

Figure 2. Equator-Crossing Longitude Grids Following PRM Delay and PJ02 Safe Mode Entry

were available on the morning of October 19, 2016. However, the main purpose of the contingency trajectories depicted in Figure 2 was to support Juno operations through the post-PJ-02 orbit trim maneuver (OTM) design[5] and subsequent PJ-03 science pass, so an end-to-end trajectory was not immediately required.

Stop-Gap Reference Trajectory

The temporary trajectory update developed in the wake of the PJ-02 safe mode event was sufficient for short-term planning activities, but, ultimately, a longer-term reference trajectory was required to support science, operations, and navigation activities while anomaly response teams at JPL and Lockheed Martin investigated root cause and potential mitigation strategies for the sticking latch valves that prompted PRM's indefinite delay. So, in the week following the PRM delay, the Juno Navigation Team developed a "stop-gap" reference trajectory that would maintain the Juno spacecraft in its 53-day capture orbit for the foreseeable future. As illustrated in Figure 3, this updated trajectory's 20 science passes build up the equator-crossing longitude grid in a manner similar to the planned 14-day science orbits. In this proposed mission architecture, the spacecraft would perform a deorbit maneuver at Apojove-21, i.e., APO-21, and impact Jupiter at PJ-22 on September 11, 2019. This deliberate impact was required to avoid a solar eclipse that would, otherwise, occur inbound to PJ-23 in early November 2019. As a solar-powered spacecraft, Juno would be unable to survive this eclipse and deorbit was necessary to meet planetary protection requirements, relative to the Galilean satellites. A detailed discussion of solar eclipse phenomena is presented in a later section. The proposed stop-gap trajectory was adopted as the Juno reference trajectory in late October 2017 and would remain in use for nearly five months.

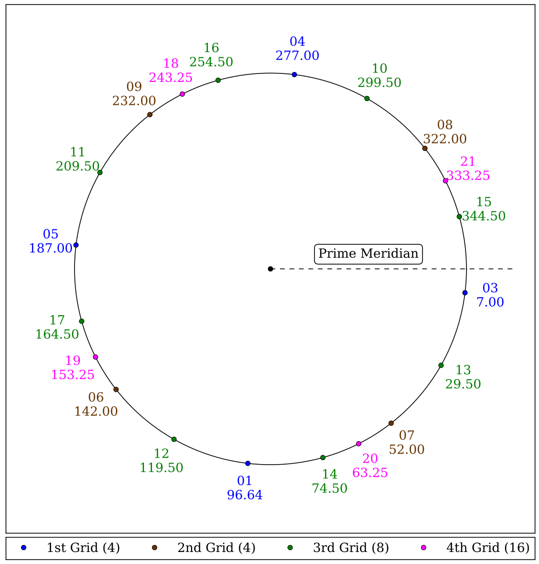


Figure 3. Equator-Crossing Longitude Grid for the Stop-Gap Reference Trajectory

TRAJECTORY DESIGN TRADE STUDY

Immediately following the decision to delay PRM, the Juno team launched a project-wide trade study of potential orbital architectures to support science operations for the remainder of the mission. A wide range of trajectory options were considered to accommodate the uncertain timeline and outcome of the ongoing main engine propulsion system investigation, but, for any potential trajectory option to be considered feasible, it had to satisfy the following set of fundamental mission constraints:

- 32-perijove, evenly-spaced longitude grid (successively finer "subgrids" preferred)
- Perijove passes must be visible by Goldstone Deep-Space Network (DSN) complex
- Inclination = $90° \pm 10°$
- 3500 km $\leq$ perijove altitude $\leq$ 8000 km
- No solar eclipses of any duration

The final four constraints were consistent with pre-launch requirements, while the 32-orbit constraint was a function of the Juno science team's preference to achieve a final equatorial longitude grid with a resolution consistent with the 14-day science orbit architecture. By combining a range of PRM epochs (including no-PRM cases) with a number of science orbit periods of interest, the Juno Navigation Team was able to analyze 15-20 potential candidate reference trajectories with widely-varying characteristics. All trajectory options discussed in this analysis are ΔV-optimal and were computed using the COSMIC multi-leg trajectory optimization application provided as part of the Jet Propulsion Laboratory's MONTE mission design and navigation software.[6]

PRM Epoch

When the reference trajectory redesign study was initiated, it was presumed that at least several months would be required to complete the main engine anomaly investigation and then design, test, and implement any future PRM burn. Thus, it was assumed that it would not be feasible to perform PRM as early as PJ-03 (December 11, 2016) or PJ-04 (February 2, 2017). It was also determined PJ-09, which occurs during solar conjunction, was not a viable option. The following PRM options received varying degrees of consideration during the course of the trade study:

- PJ-05 (March 27, 2017)
- PJ-06 (May 19, 2017)
- PJ-07 (July 11, 2017)
- PJ-08 (September 1, 2017)
- PJ-10 (December 16, 2017)

Of course, the no-PRM option also received a great deal of consideration during the trajectory redesign investigation.

Science Orbit Period

The science orbit period option space was largely dictated by 1) the performance envelope of a potential PRM burn and 2) the constraints on longitude grid build-up and Goldstone visibility listed above. Prior to PRM, all of Juno's previous main engine burns – two deep-space maneuvers[2] and JOI – were all performed as regulated burns in which the propulsion tank pressures were continuously maintained as the main engine fired. However, given the uncertain performance of the check valves that prompted the PRM delay, the main engine anomaly response team quickly determined that, if PRM was to be executed, it should be performed as a blow-down maneuver. Propulsion system analysis indicated that a PRM blow-down burn could generate enough ΔV to, at best, reduce Juno's orbital period to 18-19 days. Multi-PRM concepts were briefly discussed, but were quickly determined to be overly-complex and did not receive serious consideration. Therefore, in the early days of the trajectory design trade study, it was determined that Juno would never reach its planned 14-day science orbit and only orbits with periods greater than or equal to 20 days would be considered going forward. It was also decided that attempting PRM would only be worthwhile if a meaningful reduction in orbital period could be achieved. Consequently, orbital periods larger than 35 days were also not considered.

The Juno Gravity Science experiment relies upon two-way Ka-band radiometric tracking data to make precise measurements of Jupiter's gravity field. And, while a number of DSN stations are equipped with a Ka-band downlink, currently, only Goldstone's DSS-25 station is capable of both Ka-band downlink and uplink. Thus, the Juno mission has a strict science requirement that states that all science perijove passes must occur in view of the Goldstone DSN complex. To satisfy this requirement, it is necessary to first define a synodic period-like quantity, P_{syn}, given by,

$$\frac{1}{P_{syn}} = \frac{1}{P_{rot}} - \frac{1}{P_{syn,E-J}} \tag{1}$$

where P_{rot} is the Earth's rotational period and $P_{syn,E-J}$ is the Earth-Jupiter synodic period. Thus, P_{syn} is computed as,

$$\frac{1}{P_{syn}} = \frac{1}{1 \text{ day}} - \frac{1}{398.8 \text{ days}} = \frac{1}{1.00251 \text{ days}} \tag{2}$$

If the product of the science orbit period and P_{syn} is an integer, then ensuring Goldstone visibility for a single perijove pass will, implicitly, ensure Goldstone visibility for all perijove passes. Note that, to be concise, all orbital periods in this paper are referred to as integer values, but can be divided by P_{syn} to obtain their preferred periods, from a Goldstone visibility standpoint, e.g., "53-day orbits" are, in actuality, "52.867-day orbits."

The final requirement levied on the science orbit period as part of the reference trajectory re-design study stipulated that any orbit period considered should yield an equator-crossing longitude grid consisting of 32, evenly-spaced perijove passes. Furthermore, the Juno Science Team also preferred that, like the 14- and 53-day science orbits, the longitude grid be constructed with a series of successively smaller "sub-grids" to ensure adequate global coverage of Jupiter at all stages of the mission. From a mission design standpoint, it is also desirable to minimize ΔV expenditure as much as possible, by ensuring that the longitude difference between subsequent nodes in the equatorial longitude grid is relatively close to the angular rotation of Jupiter over the course of the orbit period in question. The angular rotation of Jupiter, $\Delta\alpha_J$, expressed as an effective difference in west longitude, is given by,

$$\Delta\alpha_J = (-P\omega_J) \bmod 360^\circ \tag{3}$$

where P is the science orbit period, ω_J is Jupiter's spin rate (-870.536 deg/day), and mod is the modulo operation. The designed longitude difference for several science orbits of interest with periods, 20 days $\leq P \leq$ 35 days (plus two no-PRM cases), are compared to their corresponding effective angular rotation of Jupiter in Table 1. Note that a designed west longitude difference of

Table 1. ΔWest Longitude Difference for Various Science Orbit Periods

Period (days)	$\Delta\alpha_J$ (deg)	Designed ΔW. Lon. (deg)	| Difference | (deg)
11	191.88	192.00	0.12
14	276.94	270.00	6.94
20	87.06	90.00	2.94
21	235.42	236.25	0.83
24	320.47	315.00	5.47
27	45.53	45.00	0.53
53	302.71	270.00	32.71
54	91.07	90.00	1.07

270 degrees is analogous to a 90-degree longitude shift except that the equatorial grid is built up in a counter-clockwise manner. Designed longitude shifts of 45 and 235 degrees are used to construct sub-grids of eight perijove passes – instead of four in the case of 90/270-deg longitude shifts – but were still acceptable to the Juno Science Team. The 21-day science orbit differs considerably from the other options in that it employs 236.25-degree steps in west longitude (123.75 degrees east longitude) so each set of three perijove passes divides the equatorial grid approximately into thirds. This longitude build-up strategy was less desirable from a science perspective, but, like the 14-day science orbits, was very desirable from an operations perspective because it aligned well with a 7-day workweek. Lastly, while the 54-day option takes longitude steps that are significantly closer

to its corresponding effective angular rotation of Jupiter than the 53-day case, the ΔV savings were not significant because 1) both orbits are large and satellite perturbations can dramatically affect the period from orbit to orbit and 2) the ΔV required to increase the orbital period from 53 to 54 days dominated any propellant savings that might have otherwise been realized. Thus, the 53-day orbit was the primary no-PRM option considered as part of the reference trajectory redesign trade study.

Solar Eclipse Geometry

Of all of the trades considered during the Juno reference trajectory redesign studies, perhaps no issue was weighed more heavily than solar eclipse analysis and potential avoidance strategies. Previous iterations of the Juno reference trajectory featuring 11-day and 14-day science orbits possessed mission end times in October 2017 and February 2018, respectively. However, delaying PRM necessitated investigating much longer mission durations. Additional analysis during the reference trajectory redesign trade study uncovered the potential for solar eclipses to occur between approximately July 2019 and March 2020 – a period informally referred to as "eclipse season." An illustration depicting the relative geometry of the Sun, Jupiter, and Juno's orbital plane at the end-of-mission (EOM) locations for various candidate reference trajectories appears in Figures 4. The large gray circle represents Jupiter's 11.86-year heliocentric orbit as viewed from the north ecliptic pole. The black dots and red lines depict Jupiter's location and the orbital plane of Juno's polar orbit, respectively, at various epochs of interest. The shaded gray region indicates the notional region of Jupiter's orbit where Juno's orbital plane is nearly aligned with the Sun-Jupiter line and solar eclipses can occur, i.e., eclipse season.

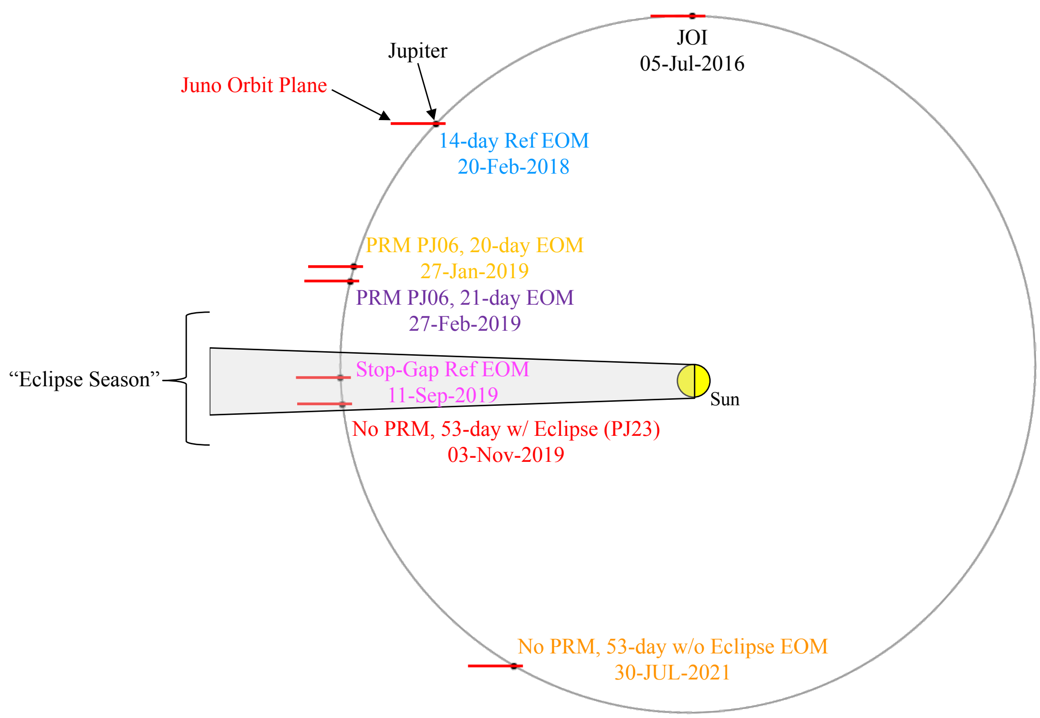


Figure 4. Heliocentric Illustration of "Eclipse Season" Geometry, *Figure Not to Scale*

At the top of the figure, it is apparent that Juno's Jupiter-centric orbital plane was nearly orthogonal to the Sun-Jupiter line when the spacecraft inserted into orbit on July 5, 2016. Progressing counter-clockwise around the figure, the nominal end-of-mission geometry for the planned 14-day reference trajectory appears in blue and two example trajectories from the trajectory redesign trade study – 20- and 21-day science orbits with PRM performed at PJ-06 – appear in yellow and purple, respectively. As the Juno mission duration increases, Jupiter advances further in its heliocentric orbit, and the spacecraft will, eventually, encounter eclipse season. The endpoint of the stop-gap reference trajectory that terminates at PJ-22 to avoid solar eclipse is shown in magenta. If the stop-gap reference trajectory did not deorbit, it would encounter a solar eclipse inbound to PJ-23, indicated in red. For reference, the end-of-mission location for a 53-day, no-PRM trajectory that completes the full 32-perijove longitude grid and terminates in July 2021 appears in orange near the bottom of the figure.

When a candidate trajectory encounters eclipse season, the timing, duration, and number of eclipses are largely a function of the science orbit period. Fundamentally, as Juno's orbit period decreases, the spacecraft crosses Jupiter's orbital plane closer to the planet, increasing the apparent size of Jupiter which, in turn, leads to longer eclipse seasons, and eclipses that are more frequent, but shorter in duration. Figure 5 illustrates this phenomenon for four science orbit periods of interest. Each trajectory is plotted in a XZ-projection of a Sun-Jupiter rotating frame with the umbral shadow cone in green and umbral entrances and exits denoted with blue and magenta dots, respectively. A YZ-projection, that is, looking toward the Sun along the Sun-Jupiter line, for the same four trajectories is presented in Figure 6. The corresponding umbral eclipse data is tabulated in Table 2.

Table 2. Umbral Eclipses for Various Orbit Periods

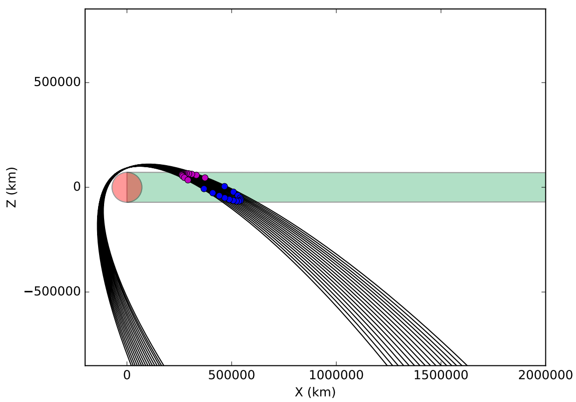
Period (days)	Number of Eclipses	First Eclipse	Final Eclipse	Eclipse Duration (hrs)		
				Min.	Max.	Mean
20	14	25-Jul-2019	07-Apr-2020	0.93	3.50	2.64
21	12	25-Jul-2019	15-Mar-2020	0.77	3.74	2.84
27	7	31-Aug-2019	09-Feb-2020	1.32	5.12	3.89
53	1	02-Nov-2019	02-Nov-2019	11.88	11.88	11.88

As expected, the shorter-period orbits possess significantly more, shorter-duration eclipses, while the 53-day science orbit has a single eclipse that is nearly 12 hours in duration.

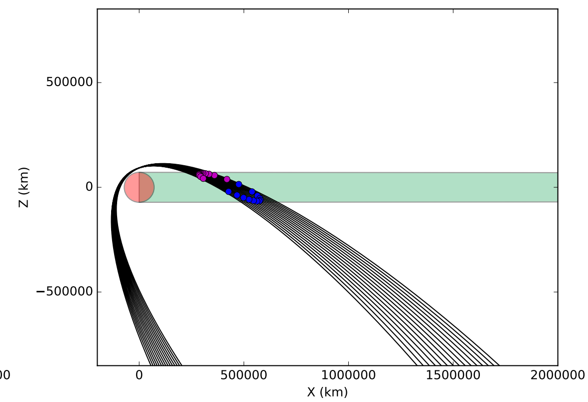
Eclipse Avoidance Strategies

Regardless of the number or duration of eclipses encountered, as a solar-powered spacecraft, all of the potential eclipses analyzed in this investigation are considered likely to be mission-ending for Juno. Thus, it quickly became apparent during the trajectory redesign trade study that any acceptable trajectory options must avoid solar eclipse entirely – either by manipulating the orbit geometry to pass around any potential eclipses or by terminating the mission prior to entering eclipse.

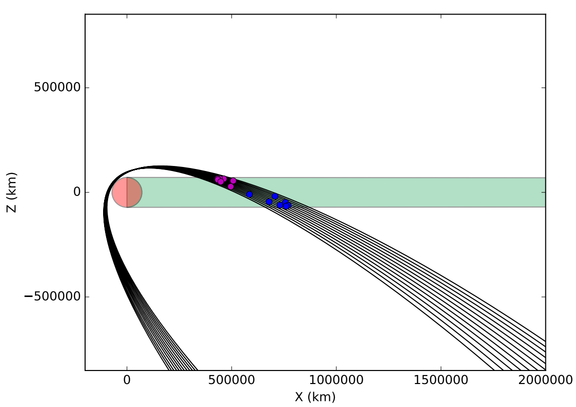
For the 53-day candidate reference trajectory, there was a single, long-duration eclipse that must be avoided. As Jupiter follows its orbital path around the Sun, the right ascension of the ascending node (RAAN) for Juno's orbit has an apparent drift when viewed in a Sun-Jupiter Rotating reference frame. By carefully modulating Juno's orbital inclination, which, in turn, controls its nodal drift rate,



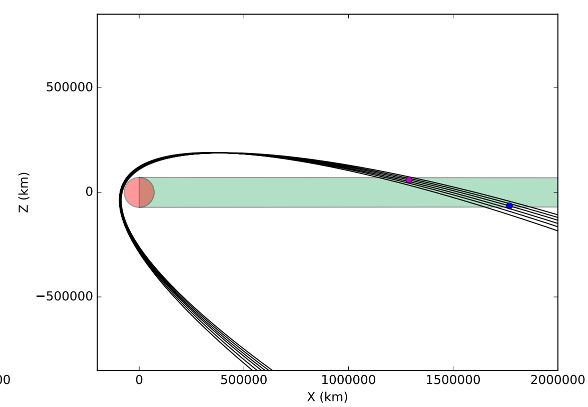
(a) 20-day Orbits



(b) 21-day Orbits



(c) 27-day Orbits

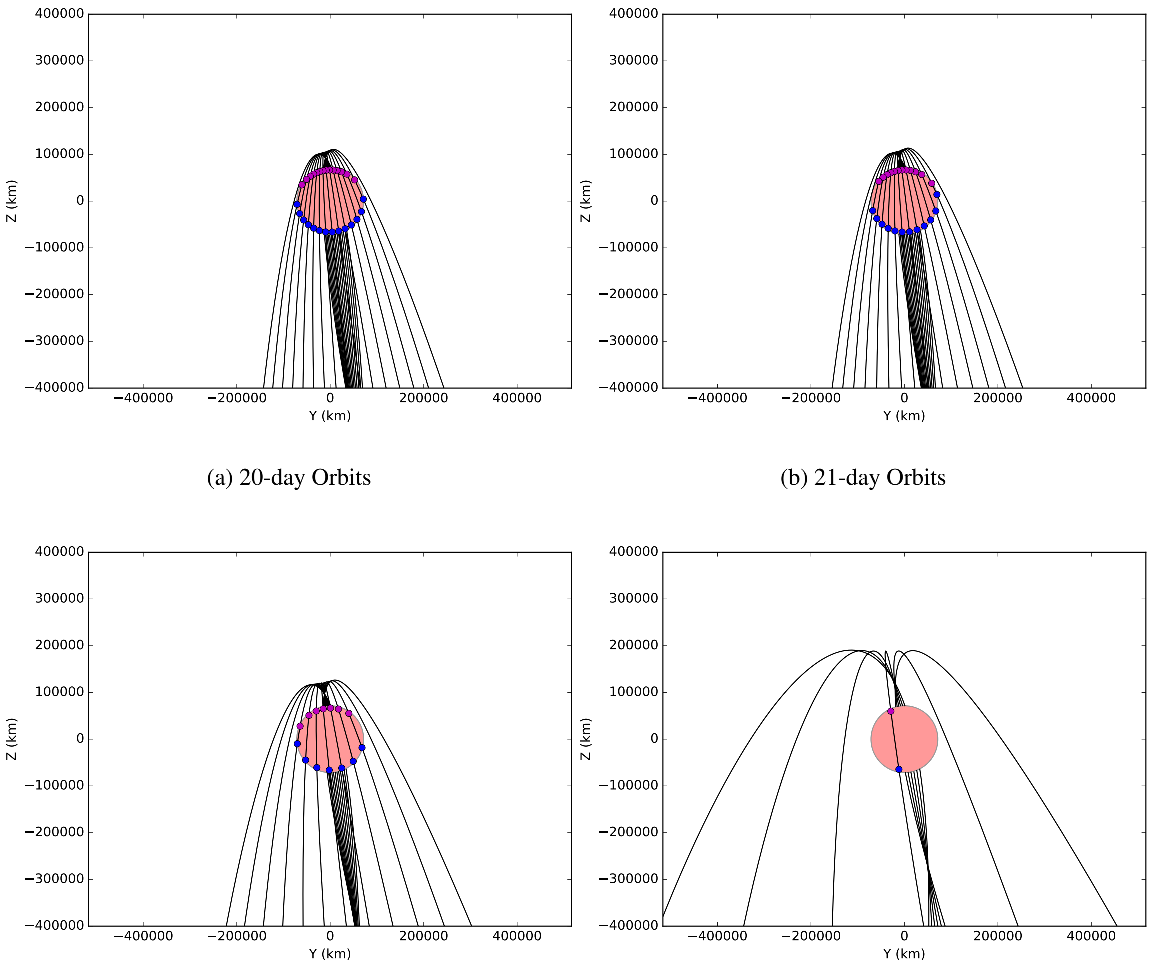


(d) 53-day Orbits

Figure 5. Eclipse Geometry for Various Science Orbit Periods, Sun-Jupiter Rotating Frame, XZ-Projection

it was determined that it was possible to "step over" the umbral cone by placing the two perijove passes in question on either side of the solar eclipse. A comparison of example 53-day trajectories with and without a solar eclipse is presented in Figure 7. For the 53-day trajectory, solar eclipse avoidance is achieved via a series of apojove maneuvers – up to and including APO-21 – to ensure that the spacecraft does not enter eclipse inbound to PJ-22. Then, at APO-22, a large, 50-60 m/s, maneuver is leveraged to change the orbital plane geometry – including an inclination increase of 4-5 degrees – and avoid eclipse entry inbound to PJ-23. The size of the inclination change required to avoid eclipse and, in turn, the corresponding APO-22 eclipse avoidance maneuver ΔV magnitude, depend directly on the maximum inclination constraint enforced as part of the trajectory redesign trade study.

While the eclipse avoidance strategy is relatively straightforward for science orbits as long as 53 days, the process is significantly more complicated for shorter-period orbits that may pass through umbral shadow many times. In Juno's case, there is not nearly enough onboard propellant to perform the very large inclination changes necessary to shift many eclipsed perijove passes so that they lie



(a) 20-day Orbits

(b) 21-day Orbits

(c) 27-day Orbits

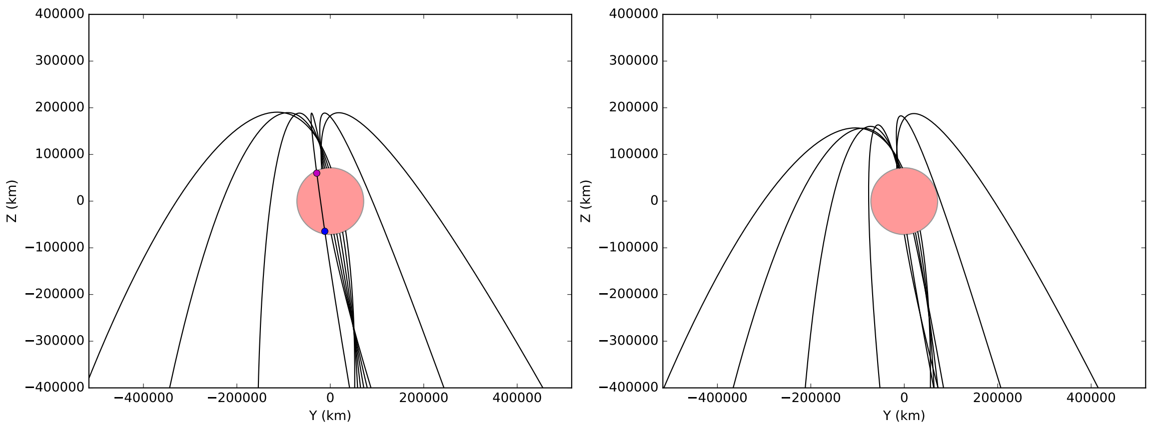
(d) 53-day Orbits

Figure 6. Eclipse Geometry for Various Science Orbit Periods, Sun-Jupiter Rotating Frame, YZ-Projection (View Toward Sun)

on either side of the umbral cone. Additionally, the project briefly explored the feasibility of using a low-altitude Callisto flyby to increase the orbital period prior to entering eclipse season. However, preliminary analysis indicated that the Callisto gravity-assist in question could not increase the period to the extent that a large eclipse avoidance apojove maneuver would be possible. Thus, it was concluded that solar eclipse avoidance was infeasible for any proposed science orbit period less than 53 days.

Summary of Candidate Reference Trajectories

The solar eclipse avoidance requirement combined with a strong desire by the Juno Science Team to complete the 32 science perijove passes, consistent with the 14-day science orbit reference trajectory, established strict bounds on combinations of potential PRM epochs and science orbit periods. As the main engine anomaly investigation proceeded, it became apparent that the project would not have sufficient time to plan and execute a PRM burn at PJ-05. Additionally, PJ-08 and



(a) With 11.88-hour Eclipse

(b) Without Eclipse

Figure 7. 53-day Orbit Eclipse Avoidance Geometry, Sun-Jupiter Rotating Frame, YZ-Projection (View Toward Sun)

PJ-10 were eliminated as potential PRM locations by the Juno Science Team due to the unfavorable solar geometry associated with that portion of Jupiter's heliocentric orbit. The 24- and 27-day science orbit periods were also removed from consideration because they offered no significant science or operational advantages over the 20- and 21-day options.

Ultimately, the Juno trajectory design trade study focused on two candidate PRM epochs in May 2017 and July 2017 – PJ-06 and PJ-07, respectively – and three potential science orbit periods – 20 days, 21 days, and 53 days. Trajectory information is aggregated for a representative set of reference trajectory options in Table 3. The 14-day reference and 53-day stop-gap trajectories are also included for reference. From the table, it is observed that, as the orbit period increases, third-

Table 3. Trajectory Options Summary

Period (days)	PRM Date	W. Lon. Shift (deg)	Max. Inc. (deg)	End of Mission	Pre-Eclipse Science PJs	Avail. DV Mean (m/s)
14	PJ02 (10/19/16)	270	90.6	2/20/18	70	169
20	PJ06 (5/19/17)	90	93.6	1/27/19	42	232
21	PJ06 (5/19/17) PJ07 (7/11/17)	236.25 236.25	93.8 94.3	1/27/19 3/31/19	40 38	233 218
53	N/A N/A	270 270	98.0 105.5	9/11/19 7/30/21	20 Avoids*	336 124

*Includes 53.0 m/s eclipse avoidance maneuver at APO-22

body effects increase the maximum orbital inclination. For the 20- and 21-day science orbit options, the maximum inclination is well within the $90° \pm 10°$ science requirement. The 53-day science orbit option that includes an APO-22 eclipse avoidance maneuver clearly violates this constraint, reaching a maximum inclination of 105.5 degrees. As anticipated, the 20- and 21-day options require a smaller PRM burn than the 14-day reference trajectory, yielding significant savings with respect to mean ΔV usage. Conversely, while the 53-day candidate trajectory expends no propellant on a PRM burn, it expends significantly more propellant than the 14-, 20-, and 21-day trajectories due to 1) frequent apojove maneuvers to maintain the perijove altitude below the 8000 km requirement and 2) the large eclipse avoidance maneuver. Lastly, from an operational standpoint, it should be noted that a full 32-orbit science campaign from a 53-day orbit is more than two years longer than all of the trajectory options that implement a PRM and the 53-day stop-gap reference trajectory.

As the latch valve anomaly investigation and reference trajectory redesign study stretched into February 2017, the Juno project determined that there was not sufficient preparation time to implement a potential PRM at PJ-06. It was also determined that the operational advantages of the 21-day science orbits outweighed the preferred longitude build up associated with the 20-day orbital period. Consequently, a 53-day science orbit and a trajectory implementing PRM at PJ-07 to achieve 21-day science orbits were selected as the final two candidate reference trajectories. In mid-Februrary of 2017, following several months of analysis by teams across the Juno project, it was ultimately decided – by the project and NASA headquarters – that Juno would forgo an attempt at PRM and would remain in 53-day science orbits for the duration of the mission.

53-DAY REFERENCE TRAJECTORY

Following the decision to not to implement PRM, there were still several topics specific to 53-day science orbits to be explored, namely, developing strategies to accommodate solar conjunctions and maintain the inclination and perijove altitude within the mission requirements.

Accommodating Solar Conjunction

The frequency with which solar conjunction occurs in Juno's 53-day science orbit trajectory is calculated by dividing the Jupiter's synodic period by Juno's orbital period, i.e.,

$$\frac{398.8 \text{ days}}{52.867 \text{ days}} \approx 7.54 \tag{4}$$

The resulting ratio indicates that the Sun-Earth-Jupiter conjunction geometry repeats approximately every 7.5 Juno orbits. Unfortunately, in Juno's case, the repeating solar conjunction cadence is closely aligned with perijove/apojove events and the spacecraft encounters conjunction near the following apses: PJ-09, APO-16, PJ-24, and APO-31. Juno OTMs are typically performed 7.5 hours after perijove, but, to accommodate solar conjunction, OTM-09 and OTM-24 are moved to perijove + 7 days and perijove + 5 days, respectively, to ensure that the maneuvers are performed at Sun-Earth-Probe (SEP) angles greater than 3 degrees and the spacecraft can be reliably tracked by the DSN. Deterministic apojove maneuvers – at APO-08 and APO-23 – are not permitted prior to the perijove conjunctions. Lastly, apojove maneuvers are also prohibited during solar conjunctions at APO-16 and APO-31. A detailed discussion of deterministic and statistical maneuver locations is provided by Stumpf et al.[5]

Maximum Inclination Trade Study

In Juno's highly-elliptical, 53-day orbit, third-body gravitational effects dramatically increase the orbital inclination through the first half of the mission – approximately until eclipse season – and decrease the inclination through the latter half of the mission. To avoid solar eclipse, the APO-22 eclipse avoidance maneuver introduces an additional increase in inclination of approximately

4-5 degrees. If the maximum inclination constraint is not enforced, the inclination increases from 90.6 degrees at PJ-04 to 101.2 degrees and 105.5 degrees pre- and post-APO-22, respectively, as depicted by the magenta curve in Figure 8. Consequently, to ensure that the 90° ± 10° constraint is

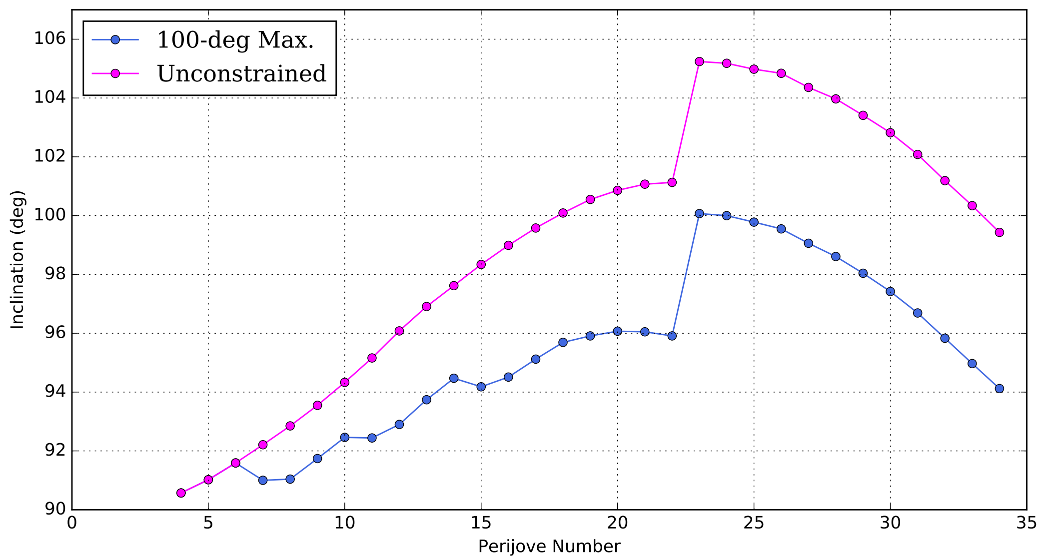


Figure 8. 53-day Orbit Maximum Inclination Comparison

not violated, the pre-APO-22 inclination must be limited to 95.5 degrees as illustrated by the blue curve. Maintaining the inclination within the mission requirements via frequent apojove maneuvers results in a significant total mission ΔV increase of nearly 60 m/s compared to the unconstrained case. The Juno science and spacecraft operations teams concluded that there was no significant penalty associated with relaxing the maximum inclination requirement and, thus, the project chose to adopt the unconstrained orbital inclination strategy.

Perijove Altitude Trade

In addition to the constraint on orbital inclination, recall the that Juno reference trajectory is also required to maintain the perijove altitude such that 3500 km $\leq$ perijove altitude $\leq$ 8000 km. To address this requirement in the presence of third-body effects, that would otherwise significantly increase the perijove altitude over the course of the mission, three distinct perijove altitude maintenance strategies were developed:

1. Maintain altitude at 3500 km (when possible)
2. Maintain altitude near 8000 km (when possible)
3. Allow altitude to range between 3500 km and 8000 km

The perijove oblate altitude profiles associated with the three strategies appear in green, orange, and magenta, respectively, in Figure 9. Note that, in all three strategies, the perijove altitude is allowed to increase prior to APO-22 so that the apojove maneuver can leverage a large perijove altitude decrease in conjunction with a large inclination increase to step over the umbral cone and avoid solar eclipse.

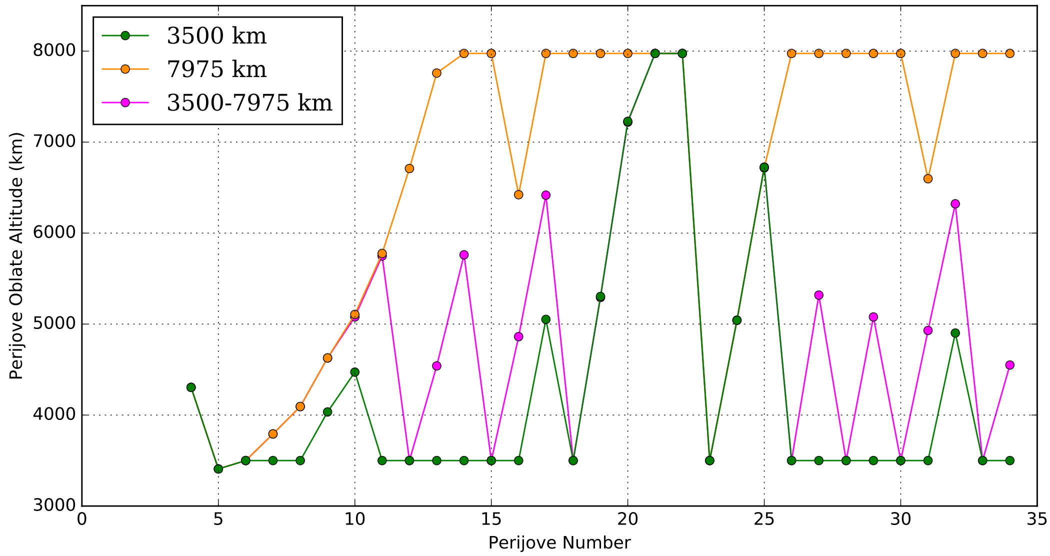


Figure 9. 53-day Orbit Perijove Altitude Comparison

In strategy 1), maneuvers are employed at most apojoves to reduce the altitude at the upcoming perijove to 3500 km. Peaks in the curve occur when one or more apojove maneuvers are not permitted due to solar conjunction. Inversely, strategy 2) leverages maneuvers at most apojoves to maintain the upcoming perijove altitude at 7975 km (to provide margin against the 8000-km requirement). In this approach, the perijove altitude is allowed to rise naturally through PJ-13 and altitude correction begins with the APO-13 maneuver. Troughs in the orange curve occur prior to apojove locations where maneuvers are prohibited due to operational constraints imposed nears solar conjunctions. In the third altitude maintenance strategy, maneuvers are utilized every 2-3 apojoves to maintain the perijove altitude between 3500 km and approximately 6500 km. As a result, strategy 3) requires fewer apojove maneuvers than the other strategies, but the individual maneuvers are, generally, significantly larger in terms of ΔV. A ΔV budget analysis for the three perijove altitude maintenance strategy determined that the total mission mean ΔV usage was approximately equal for strategies 1) and 2) and a mean ΔV savings of 13 m/s was realized using strategy 3). Ultimately, the Juno project determined that maintaining the perijove altitude at 3500 km would yield meaningful scientific gains, particularly for the gravity science experiment, that outweighed the relatively modest gains in propellant margin achieved by maintaining the perijove altitude near 8000 km.

53-day Reference Trajectory Details

The outcomes of the maximum orbital inclination and perijove altitude design trades were incorporated into an updated Juno reference trajectory featuring 53-day science orbits that was approved and released publicly by the Juno project in mid-March 2017. The equator-crossing longitude grid associated with the final 53-day reference trajectory design appears in Figure 10. Timing and geometry details for each perijove and equator-crossing included in the Juno reference trajectory are presented in Table 4. Perijove and equator-crossing epochs are expressed in ephemeris time (ET) and the perijove velocity and inclination are with respect to an inertial, Jupiter-centered, “Jupiter Mean Equator and Equinox of Epoch” coordinate frame. The latitude, longitude, and oblate altitude are relative to a body-fixed, i.e., “System III,” coordinate system fixed to an oblate spheroid Jovian

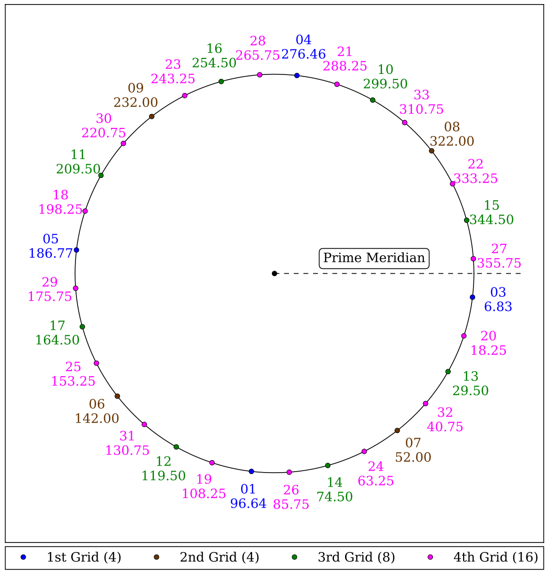


Figure 10. Equator-Crossing Longitude Grid for the 53-day Reference Trajectory

shape model. Impulsive ΔV magnitudes for all post-perijove OTMs and apojove maneuvers are also included. Post-perijove maneuvers take place 7.5 hours after perijove – except in the case of solar conjunction – and apojove maneuvers generally occur 7 days prior to apojove to best support the project's operational cadence and enable backup maneuver opportunities in off-nominal scenarios.[5] The trajectory includes an extra perijove pass, PJ-34, to replace a missed science longitude, if necessary. A 19.2 m/s APO-34 deorbit maneuver results in a PJ-35 Jupiter impact on July 30, 2021.

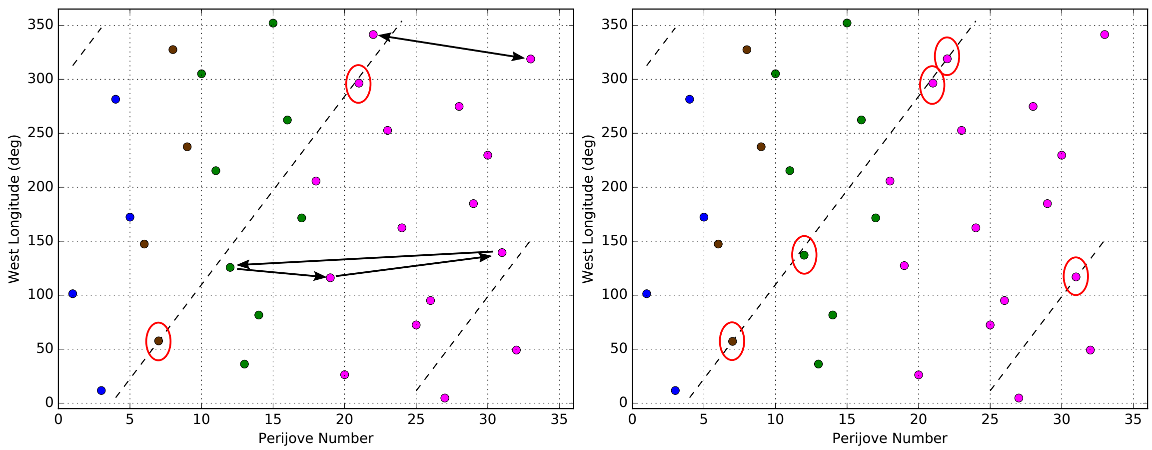
FUTURE TRAJECTORY DESIGN CONSIDERATIONS

Despite completing the design of an updated, 53-day reference trajectory, the Juno project continues to explore a number of design trades that could, potentially, be included in future iterations of the reference trajectory. The most notable studies currently under investigation include a strategy to target flyovers of Jupiter's Great Red Spot and to set up an occultation of the Earth by Jupiter.

Great Red Spot Longitude Targeting

Jupiter's Great Red Spot is a region of scientific interest to the Juno mission and broader scientific community. The enormous storm is situated at approximately -20 degrees latitude and revolves around the planet at a current rate of approximately 0.33 degrees/day. Serendipitously, the current Juno reference trajectory yielded a nearly-direct flyover of the GRS near PJ-07 on July 11, 2017 and will pass close to the GRS again near PJ-21 on July 21, 2019.

In the event that the Juno Science Team requests additional GRS flyovers over the course of the mission, the Juno Navigation Team has developed a graphical technique for selecting pairs or trios of equator-crossing longitudes that can be "swapped" to yield additional GRS flyovers. The graphical method for determining candidate "longitude swaps" is illustrated in Figure 11. GRS-crossing west longitude is plotted as a function of perijove number and the marker color is consistent with the subgrid coloring in the equator-crossing longitude grid presented in Figure 10. The dotted line denotes the linear GRS trend line and close GRS passages are denoted with red ellipses. To



(a) Current Reference Trajectory

(b) With Additional GRS Flyovers

Figure 11. Proposed GRS "Longitude Swapping" Strategy

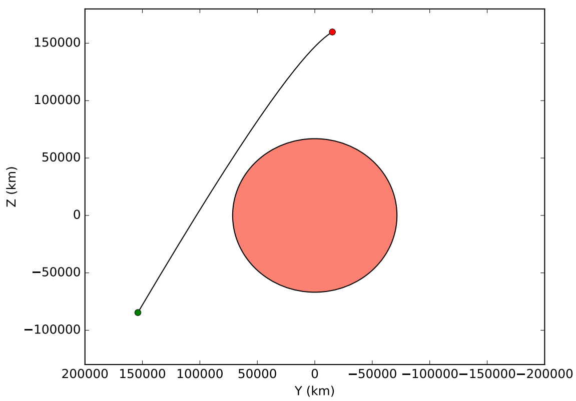
generate additional GRS flyovers, pairs or trios of longitudes are swapped to move one or more markers closer to the GRS trend line. In this example, four longitude swaps, denoted with black arrows, are able to generate three additional opportunities for low-altitude GRS observation for a similar total mission ΔV. This GRS targeting strategy is very flexible and can be readily updated as GRS trending and/or the project's scientific priorities evolve over the course of the mission.

Occultation Targeting

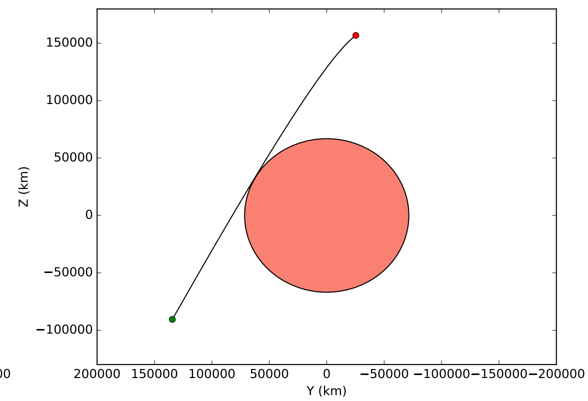
The Juno Science Team is also interested in making radiometric observations through Jupiter's atmosphere via an occultation of the Earth-Juno line by Jupiter. The current Juno reference trajectory does not include any such occultations, but an analysis of minimum Jupiter-probe-Earth (JPE) angle for the remainder mission revealed that the Earth-Juno line is closest to the Jovian limb inbound to PJ-23 on November 3, 2019. Preliminary analysis indicates that the APO-22 eclipse avoidance maneuver can be leveraged to further increase the orbital inclination and produce an occultation prior to the subsequent perijove. For example, an 8-minute occultation increases the APO-22 ΔV magnitude by approximately 15 m/s and the total mission ΔV by approximately 12 m/s. The inbound PJ-23 geometry without and with the 8-minute occultation is depicted in an Earth-Jupiter rotating frame in Figure 12. In this example, Juno moves from the green dot to the red dot and the Earth-Juno line barely skims the Jovian atmosphere. The duration of the occultation event is directly correlated with the ΔV increase at the APO-22 maneuver, so longer occultations can be designed at the cost of increased ΔV expenditure.

CONCLUDING REMARKS

The days and weeks following the scheduled PRM execution in October 2016 were a challenging time for the Juno project with the main engine pressurization anomaly, decision to delay PRM indefinitely, and safe mode entry immediately prior to the PJ-02 science pass all occurring within the span of one week. Fortunately, the Juno Navigation Team's robust trajectory design and analysis tools and anomaly-response strategies developed in the months preceding PRM enabled the team to



(a) Without Occultation



(b) With 8-minute Occultation

Figure 12. Example Occultation Targeting Strategy Inbound to PJ23

act quickly to provide stop-gap solutions in the days following the decision to delay PRM. The same capabilities allowed the exploration of wide-ranging mission concepts in support of the reference trajectory redesign trade study that, ultimately, resulted in a 53-day science orbit architecture following the decision to cancel any future attempt at a PRM burn. At the time of publication, the Juno spacecraft is healthy and has been operating nominally along its current 53-day reference trajectory since March 2017. Since arriving at Jupiter in July 2016, Juno has completed 6 out of 32 planned science passes that have already yield groundbreaking scientific discoveries.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of the entire Juno navigation team to the successful design and operation of the Juno mission to date. The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Table 4. 53-day Reference Trajectory Details

Orbit #	PJ Epoch (ET)	SEP (deg)	Obl. Alt. (km)	Lat. (deg)	Vel. (km/s)	Inc. (deg)	Eq-X Epoch (ET)	Eq-X Lon. (deg)	PJ ΔV (m/s)	Apo ΔV (m/s)
4	02-FEB-2017 12:58:18	110.76	4304.21	6.58	57.76	90.57	02-FEB-2017 13:00:49	276.45	0.30	3.77
5	27-MAR-2017 08:53:00	167.08	3404.22	7.55	58.12	91.03	27-MAR-2017 08:55:50	186.77	1.81	-
6	19-MAY-2017 06:01:54	135.41	3496.90	8.49	58.09	91.59	19-MAY-2017 06:05:06	142.00	2.79	1.09
7	11-JUL-2017 01:55:59	85.67	3500.00	9.45	58.10	92.23	11-JUL-2017 01:59:33	52.00	2.80	1.12
8	01-SEP-2017 21:50:05	42.54	3500.00	10.38	58.10	92.89	01-SEP-2017 21:54:00	322.00	0.87	-
9	24-OCT-2017 17:44:08	1.87	4034.57	11.29	57.90	93.59	24-OCT-2017 17:48:27	232.00	3.50	-
10	16-DEC-2017 17:58:46	40.79	4321.50	12.19	57.80	94.38	16-DEC-2017 18:03:27	299.50	0.62	5.48
11	07-FEB-2018 13:52:57	86.85	3500.00	13.09	58.13	95.29	07-FEB-2018 13:57:55	209.50	3.32	3.42
12	01-APR-2018 09:47:06	139.22	3500.00	13.97	58.14	96.15	01-APR-2018 09:52:24	119.50	1.92	3.83
13	24-MAY-2018 05:41:16	163.39	3500.00	14.85	58.15	97.00	24-MAY-2018 05:46:55	29.50	3.22	4.51
14	16-JUL-2018 05:18:47	109.73	3500.00	15.70	58.16	97.74	16-JUL-2018 05:24:46	74.50	4.73	4.71
15	07-SEP-2018 01:13:04	63.65	3500.00	16.56	58.17	98.43	07-SEP-2018 01:19:24	344.50	2.04	5.01
16	29-OCT-2018 21:07:24	21.53	3500.00	17.39	58.18	99.09	29-OCT-2018 21:14:04	254.50	1.98	-
17	21-DEC-2018 17:01:34	20.21	5053.94	18.14	57.58	99.69	21-DEC-2018 17:08:46	164.50	1.04	11.83
18	12-FEB-2019 16:20:56	63.99	3500.00	18.93	58.20	100.19	12-FEB-2019 16:28:14	198.25	1.03	-
19	06-APR-2019 12:15:07	112.09	5306.13	19.64	57.50	100.64	06-APR-2019 12:22:59	108.25	0.26	-
20	29-MAY-2019 08:09:22	166.67	7247.21	20.30	56.78	100.96	29-MAY-2019 08:17:49	18.25	1.69	4.33
21	21-JUL-2019 04:03:53	137.05	7975.00	20.97	56.52	101.15	21-JUL-2019 04:12:45	288.25	2.97	7.33
22	12-SEP-2019 03:41:56	86.89	7975.00	21.62	56.53	101.19	12-SEP-2019 03:51:05	333.25	1.56	52.95
23	03-NOV-2019 23:34:05	42.68	3500.00	22.42	58.26	105.49	03-NOV-2019 23:42:58	243.25	0.99	-
24	26-DEC-2019 17:00:07	0.84	5040.96	22.89	57.66	105.43	26-DEC-2019 17:09:28	63.25	7.06	-
25	17-FEB-2020 17:52:45	41.34	6727.91	23.41	57.02	105.23	17-FEB-2020 18:02:38	153.25	3.31	18.63
26	10-APR-2020 14:25:42	85.70	3500.00	24.04	58.28	105.10	10-APR-2020 14:35:14	85.75	0.16	6.79
27	02-JUN-2020 10:21:03	135.66	3500.00	24.64	58.29	104.70	02-JUN-2020 10:30:48	355.75	0.10	6.32
28	25-JUL-2020 06:16:30	168.16	3500.00	25.26	58.30	104.24	25-JUL-2020 06:26:29	265.75	3.07	5.85
29	16-SEP-2020 02:11:58	113.74	3500.00	25.90	58.31	103.73	16-SEP-2020 02:22:11	175.75	4.83	5.80
30	08-NOV-2020 01:50:48	65.98	3500.00	26.56	58.33	103.10	08-NOV-2020 02:01:15	220.75	0.43	5.33
31	30-DEC-2020 21:46:21	22.88	3500.00	27.27	58.34	102.39	30-DEC-2020 21:57:04	130.75	0.62	-
32	21-FEB-2021 17:41:39	18.38	4889.28	27.98	57.81	101.49	21-FEB-2021 17:52:56	40.75	4.53	9.39
33	15-APR-2021 13:37:35	59.89	3500.00	28.76	58.37	100.62	15-APR-2021 13:48:50	310.75	1.73	3.90
34	07-JUN-2021 09:33:12	104.96	3500.00	29.55	58.39	99.72	07-JUN-2021 09:44:44	220.75	-	19.24
35	30-JUL-2021 04:34:37	157.41	-700.00	30.47	60.16	98.82	30-JUL-2021 04:45:29	97.40	-	-